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Dynamic Response of Tall Timber Buildings to Wind Load

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Summary

In various urban locations around the world, there are examples of multi-storey buildings which have recently been constructed, or are proposed to be constructed using timber as their primary structural material. Such buildings present new challenges in design and analysis.

The Eurocode 1 analysis method for along-wind vibration is applied here to a hypothetical modern tall timber building. The results of the analysis highlight the potential for an unacceptable along-wind dynamic response to turbulent wind load, and the importance of structural damping in mitigating that response. Tests on a dowelled timber connection are also presented, which illustrate the factors which affect stiffness and structural damping in such connections.

Through analysis and experiment, this work shows several aspects of the dynamic behaviour of timber structures which will be important in the design of future tall timber buildings.

Keywords: *timber; tall buildings; wind load; dynamic behaviour; engineered timber*

1. Introduction

Several examples have appeared recently of modern urban multi-storey buildings whose primary structural material is timber. The Stadthaus in Hackney, London comprises 8-storeys of cross-laminated timber construction on a reinforced concrete podium [2]. Bridport House, another 8-storey cross-laminated timber building is under construction, also in Hackney [3]. In Skelleftea, in northern Sweden, a timber multi-storey office and car park is part of a residential development in the Ekorren district, which also includes a 5-storey timber residential block [4].

More tall timber buildings are in prospect. A particularly notable example is the Barentshus, a 20-storey building proposed for the town of Kirkenes, in northern Norway [5]. Lateral load resistance in this building is proposed to be performed by a braced external frame of glue-laminated timber elements. A consortium called LifeCycle Tower is proposing a building system, in which timber is the primary structural material, which could be used for a tower of up to 30 storeys [6].

Innovative systems for tall timber buildings have also been proposed. Researchers at the University of Canterbury [7] have modelled and tested, in collaboration with industry, a structural system for buildings of ten storeys or more using timber elements connected by prestressed steel cables.

Various factors have contributed to this return of timber to urban construction. The speed of construction of timber structures is one, along with the fact that a large part of the fabrication of the structure can be carried out in controlled factory conditions, with extensive mechanisation. The rising cost of non-renewable alternative construction materials has also had an effect.

Another factor that undoubtedly has an effect on the attractiveness of timber as a construction material is the fact that wood sourced from well-managed forests can be considered to have stored a certain amount of carbon from the atmosphere during its growth. This stored carbon can be offset against the carbon released into the atmosphere as a result of the construction and use of the building, allowing buildings to be described as 'low-carbon', 'carbon-neutral' or even 'carbon-negative'. A reduction in embodied carbon can benefit different developers in different ways, since a

reduction in carbon emissions can variously provide the developer with positive publicity, satisfy legislative requirements or simply be an achievement in itself.

Though buildings of the heights described above would not be considered tall in steel or reinforced concrete, they are at the frontier of timber construction. The relative light weight and flexibility of timber in comparison with those materials means that issues familiar to tall building designers become relevant at a lower building height in timber. In particular, there is potential for wind-induced vibration to become an important design consideration.

2. Along-wind vibration

2.1 Statistical representation of wind

Design methods for the along-wind vibration of structures have been proposed and widely applied based on the representation of wind speed as a stationary random variable [8-10]. On this basis, a power spectral density function for velocity can be defined which is constant with time, such as that

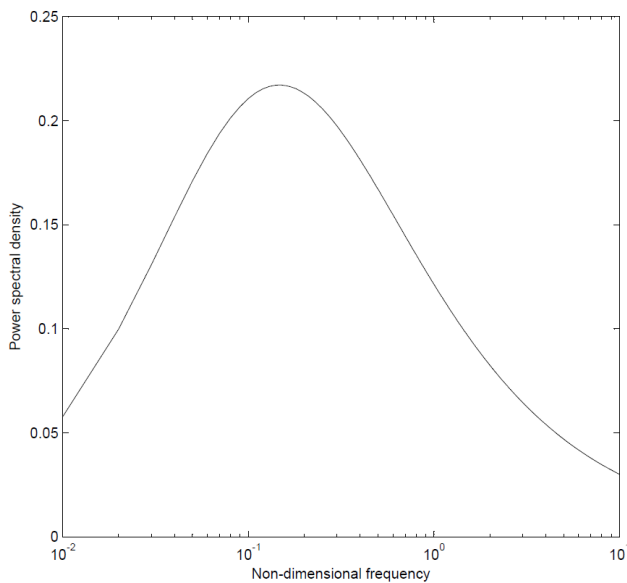


Fig. 1: Non-dimensional power spectral density function for wind velocity, after Eurocode 1 [1]

shown in Fig. 1. This can then be used in conjunction with the drag coefficient of the body subject to the wind to define a power spectral density function for force.

For a linear system, such as a slender, line-like vibrating object, a transfer function can be defined which relates the power spectral density of the displacement of the system to the power spectral density of the force applied by the wind [9, 11]. This takes the form

$$S_x(f) = H^2(f)S_F(f) \quad (1)$$

Where S_x is the spectral density function for displacement, S_F is the spectral density function for force and $H(f)$ is the mechanical admittance function for the system, derived from its mass, stiffness and damping.

This is the basis of the calculation method given in Eurocode 1 [1] for the analysis of tall buildings subject to wind load.

2.2 Correlation functions

The wind speed varies in space as well as time, and so in general the time-history of force experienced by one part of the building face will not be the same as that experienced by another. The correlation between forces on different parts of the structure will affect the behaviour of the structure as a whole.

Different correlation functions have been proposed to represent this phenomenon. Eurocode 1 gives two alternative approaches, the first of which has been used here.

2.3 Aeroelastic effects

In addition to along-wind vibration, buildings can also be subjected to vibration due to vortex-shedding and other aeroelastic effects.

The frequency of vortices shed depends on the wind speed, and the worst case for a structure is at the point when the frequency at which vortices are shed corresponds to a natural frequency of vibration of the structure. Eurocode 1 [1] states that this narrow band response at resonance, induced by the building motion has a significant effect on light structures, and that there is also broad band response, independent of building movement, which can affect heavy structures. This effect is not considered further in this paper, but the discussion of stiffness and damping in timber structures given here will apply equally to vibration induced by vortex shedding.

2.4 Acceptability of vibrations

The threshold at which vibrations are perceived by building users, and the level of vibration which is deemed acceptable for building structures has been the subject of a great deal of research. Kwok [12] provides an extensive summary of research to date. Acceleration has been widely proposed as a measure of the magnitude of vibration for use in gauging the likelihood of perception or complaint by building users. Both peak and root mean square (RMS) values of acceleration have been used.

It has been reported that the magnitude of acceleration at which vibrations are perceived varies with frequency of motion [13], and some form of frequency dependence is allowed for in design guidance [14-16].

Kwok points out that the variation of acceleration in a building subject to wind load is not sinusoidal, it is a random waveform, and although most studies have been carried out using sinusoidal vibrations, significant differences are noted in the threshold of human perception for these two types of vibration.

3. Characteristics of tall timber buildings

3.1 Weight of timber buildings

Timber-based materials vary widely in their structural performance, but, in general, timber has a stiffness-to-weight ratio approximately similar to that of steel, and about 7 or 8 times that of concrete. This means that a structural element designed to resist an imposed load on the structure, such as a core wall resisting lateral wind load, will be approximately the same weight in timber as in steel.

The density of timber is about 10% that of steel. A structural element designed to resist its own self-weight, therefore, will be significantly lighter in timber than in steel or concrete. In a floor plate in an office building, for example, a large proportion of the load supported generally comes from its own self-weight.

In a building structure, the self-weight of the floor structure contributes significantly to the weight of the structure as a whole. This is particularly true in a tall building, where diversity of use can be used to reduce the imposed loads used in design. A building with timber floors can therefore be expected to have a lower overall weight than an equivalent building with reinforced concrete or steel-concrete composite floors. This lower weight of the building can be beneficial, particularly in an urban setting, since the reduced loads on foundations can be more easily accommodated in restricted sites and transferred over underlying tunnels and other services. This is a fact that was advantageous in the design of Bridport House [3], for example, in which the foundation slab spans a water main. A lower weight can also be detrimental to structural performance, however, potentially resulting in an increase in accelerations during wind-induced vibration, and an increase in uplift forces resulting from overturning loads.

3.2 An example building

A 20-storey modern timber building has been considered. The building envelope is taken to be square in plan, 24m by 24m, with a height of 80m. Lateral loads are resisted by a glued-laminated timber external braced frame. Floor panels are solid timber cross-laminated panels. Lightweight finishes and cladding have been assumed to give a superimposed dead load of 1kN/m^2 , and the building has been taken to be used for offices, leading to a live load estimate of 3kN/m^2 . These factors contribute to a building whose overall density for dynamic calculation (using 10% of the live load as mass) is 86kg/m^3 .

Analysis has been carried out according to Eurocode 1 [1], to determine the magnitude of the RMS acceleration experienced by the building in a 10-minute period given a storm with a 5-year return period. The building is taken to be in an urban setting, with a basic wind speed of 30m/s.

The magnitude of the RMS acceleration varies with the natural frequency of the building, and with the modal damping in the first mode, the aerodynamic damping being calculated based on the above geometry. Two values of modal damping have been taken, representing the extremes of the range given for timber bridges in Eurocode 1 [1], there being no recommended values in that document

for timber building structures. Results of the analysis are shown in Fig. 2.

A line showing the maximum acceptable building response is included for the sake of comparison of responses at each damping ratio. The curve is based on that put forward by Irwin [17], since that work covered the range of frequencies of interest here. The area where the building response intersects the limit is magnified in Fig. 3.

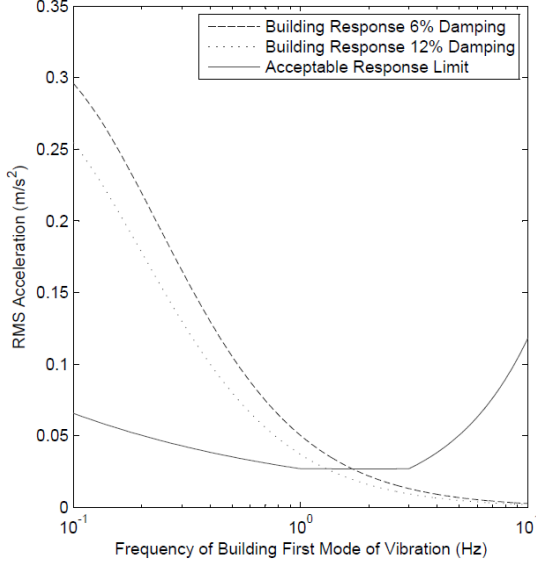


Fig. 2: Comparison of building response with limit of acceptable variation

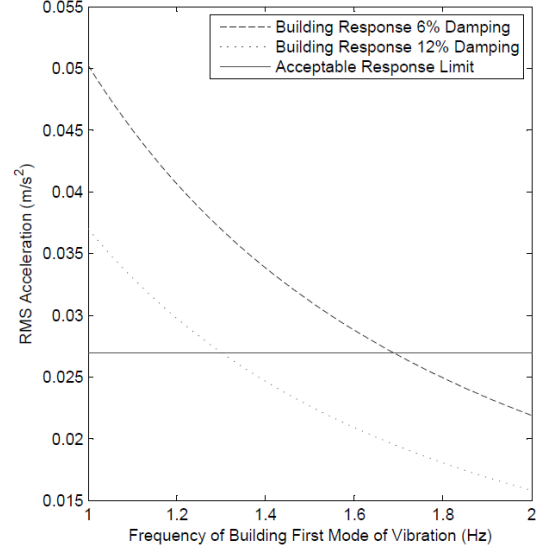


Fig. 3: Detail of Fig. 1 showing intersection of building response with limit

The plots show that the first mode frequency of the building required in order to achieve an acceptable response varies significantly with the damping ratio. Since a rise in natural frequency requires an increase in the stiffness of the lateral force resisting system in the building, it has implications for cost and use of materials in the building.

This analysis therefore highlights the importance of a clear understanding of damping in such structures.

3.3 Stiffness characteristics of timber

The stiffness of a timber structure varies according to several factors. The behaviour of timber has been described by Dinwoodie, among others, as viscoelastic [18]. Its strain therefore varies depending on the way stress is applied and removed over time.

Furthermore, an important feature of the behaviour of timber connections is the reduction in stiffness they exhibit as a result of previous loading. A timber structure therefore has the potential to exhibit a different response to a given dynamic load at different stages in its life, and a single extreme event can reduce the stiffness exhibited by the structure in subsequent events. This effect has been investigated for metal-plate connected wood truss joints by Kent [19], for sheathed wood frame walls by Shenton [20] and for joints in traditional Japanese temples by Chang [21].

3.4 Damping characteristics of timber

Damping is a measure of the energy dissipation in a component or system as it vibrates. It can be shown [22] that, for a single degree of freedom system with stiffness k taken through a cycle from displacement $+X$ to $-X$, the logarithmic decrement of damping δ is given by

$$\delta = \frac{e_d}{kX^2\Omega} \quad (2)$$

Where e_d is the energy dissipated in the cycle and $\Omega = \omega/\omega_n$ is the ratio of the excitation frequency

to the natural frequency of the system. Therefore, at resonance, the logarithmic decrement of damping is equal to the energy dissipated in a system as it is taken through a loading cycle divided by the elastic work done on the system in that cycle.

Thus, as components are combined to form a structural system, and the system is subject to a cyclic load, the total energy dissipation is made up of the sum of the energy dissipation in each component. The energy dissipation in each component will be a proportion of the work done on that component. In classical modal analysis, this combination of damping components is allowed for as the equations of motion for each mode are uncoupled.

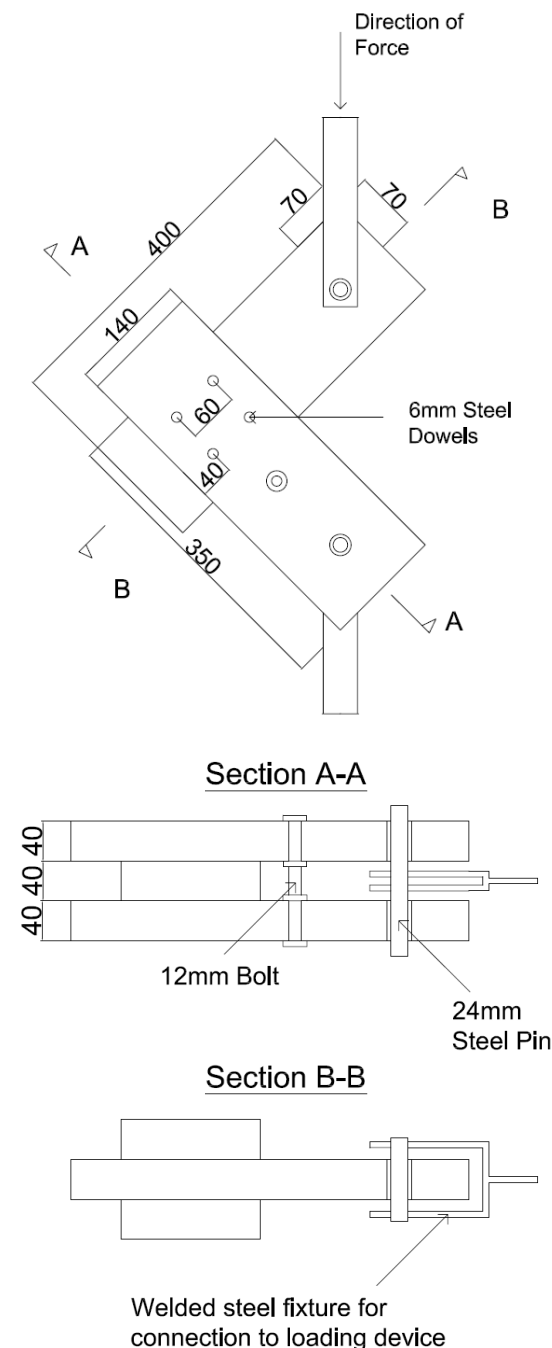


Fig. 4: Experimental specimen (dimensions in mm)

Experimental work was carried out to look at the dynamic behaviour of a simple timber structural component, a dowelled connection between members at right angles to one another, in order to investigate the nature of energy dissipation in that component.

4. Experimental work

The specimen consisted of a four-dowel connection between parallel strand lumber timber members. The geometry is shown in Fig. 4. Steel connectors attached the specimen to the loading apparatus through a pin, and a bolt acted to hold the connection together without contributing to the moment resistance of the joint. Rotation of the joint was measured by pairs of displacement transducers either side of the centre of rotation, and the applied load was measured at the loading machine.

A reversed cyclic sinusoidal variation of displacement was applied. At each increment of amplitude the displacement was applied for 10 cycles at a frequency of 0.5Hz and 10 cycles at 1Hz. A section of the load scheme is shown in Fig. 5.

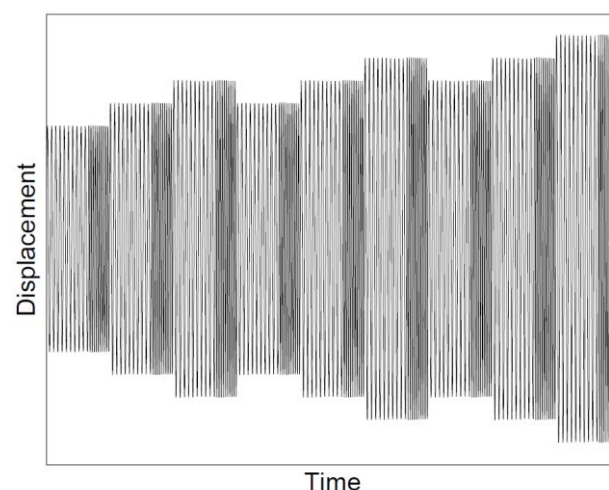


Fig. 5: Part of the reversed cyclic loading scheme

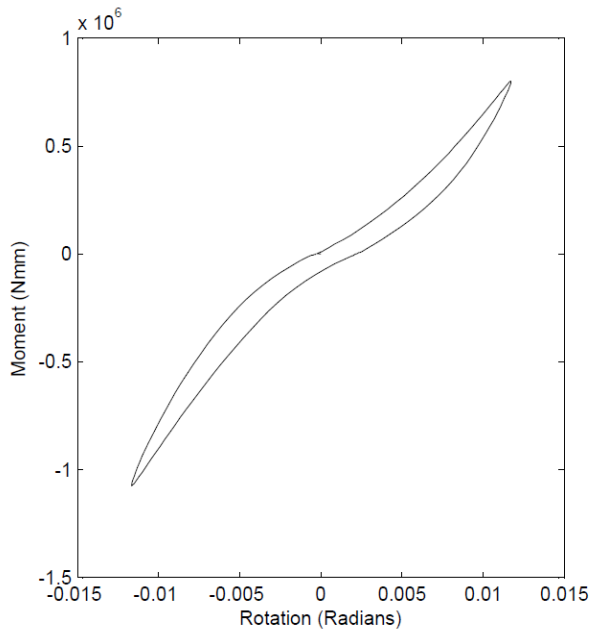


Fig. 6: Typical moment-rotation diagram

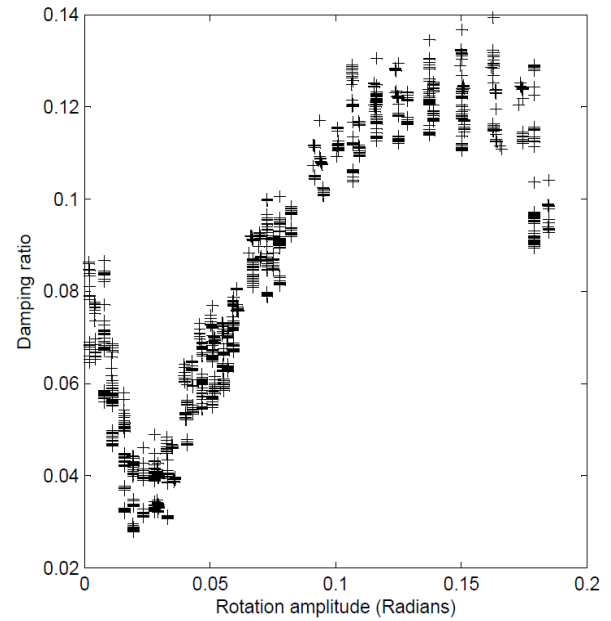


Fig. 7: Variation of measured damping ratio with amplitude of movement

The work allowed analysis of the rotational stiffness and energy dissipation characteristics of the joint, by consideration of moment-rotation diagrams, such as the one shown in Fig. 6. This highlighted several features of the dynamic behaviour of this type of joint.

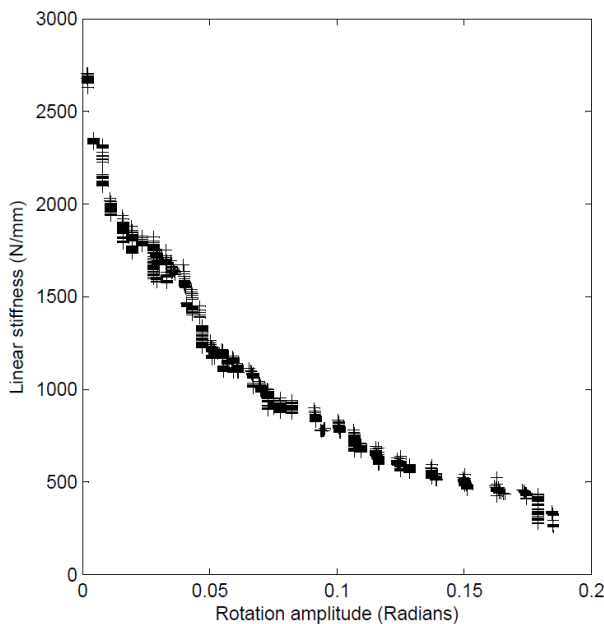


Fig. 8: Variation of secant stiffness with amplitude of movement

A variation of energy dissipation with the magnitude of the applied load was noted. Fig. 7 plots the damping ratio for the joint, calculated according to equation (2), against the amplitude of the measured rotation of the joint.

The results show a clear variation in the measured damping ratio of the joint through the test. The initial fall and subsequent increase of damping ratio with increasing amplitude of rotation is a notable feature of the behaviour of the joint, and is intended to be a subject of further investigation.

The stiffness of the joint also varied with magnitude of load applied, as shown in Fig. 8. This increase in slip in the connection through the duration of the test is thought to be a result of irreversible deformation caused by embedment of the dowels into the surrounding timber.

Furthermore, inspection of moment-rotation diagrams for similar cycles of load shows that the magnitude of the previous loading experienced by the joint has an effect on its rotational stiffness, as shown in Fig. 9.

5. Conclusion

Present day examples of urban mid-rise buildings and prospective projects around the world suggest that, in the future, timber may be used as the primary structure in buildings as tall as 30 storeys.

Analysis using a current design code, with consideration of research into human perception of vibrations, has highlighted the possibility of unacceptable dynamic response of such timber buildings as a result, primarily, of their light weight. This analysis also shows the importance of a thorough understanding of the stiffness and damping characteristics exhibited by the structural elements and joints of tall timber structures.

Through literature review and experiment, it has been noted that the stiffness characteristics of joints in timber structures vary with the duration of loading, and the magnitude of the peak loads previously experienced by the joint. This indicates that the dynamic behaviour of a timber structure would be expected to vary through its lifetime, and so care must be taken in design to assess the response of the building at all stages of its design life.

Experimental work has shown that the energy dissipation in a steel-dowelled timber connection varies as the amplitude of rotation is varied, and that this variation is evident over the whole range of rotation amplitudes considered.

This behaviour is considered to be a potential topic for further research. Further research is also intended into the combination of the dynamic response of components in a timber building, and how the energy dissipation in each component contributes to the damping in the structure as a whole.

The work presented here extends knowledge in this field by considering the sensitivity of along-wind response to a structural damping coefficient which is not prescribed in design codes. Much previous research has considered damping in timber structures under the loads and deformations associated with seismic events, whereas the experimental work shown here includes results for the smaller deformations associated with serviceability under turbulent wind load.

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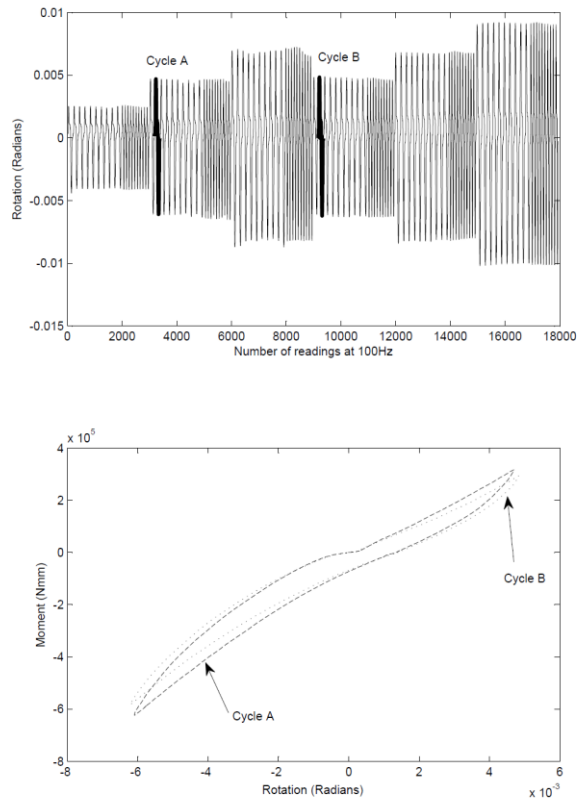


Fig. 9: Influence of previous loading on secant stiffness

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